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METHODS OF COMPENSATION FOR THE AUTOMATIC FREQUENCY CONTROL LOO--ETC(U)
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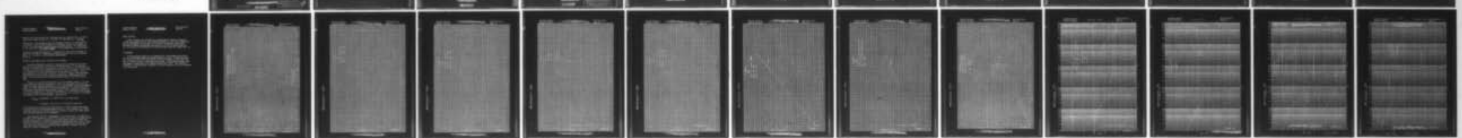

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Subject: Methods of Compensation for the Automatic Frequency Control Loop (AFC) and Automatic Phase Control Loop (APC) in the MAULER Receiver

References: (1) "Pull-In Performance of an Automatic Phase Control System in a High Noise Environment," TM-252-80

(2) "Analytical Design of Linear Feedback Controls," Newton, Gould and Kaiser, Wiley, 1957

SUMMARY

The forms of compensation in the AFC and APC loops for the Mauler receiver are discussed. Figure 1 presents the system block diagram. The equivalent linearized model is shown in Figure 2. Basic compensation considered for both AFC and APC loops are first order lag-lead networks. Effects of loop gains and corner frequencies of the compensation networks are considered parametrically.

The study is divided into three parts: (1) linearized system response to a ramp change in doppler frequency without time delay, (2) system response to a ramp change in doppler frequency, (3) loop stability analysis. Responses for (1) were computed on the digital computer. Responses computed for (2) utilized an analog computer simulation which included the non-linearity in the phase detector. The analysis under (3) includes effects of pure time delays in the IF amplifier and the discriminator.

System parameters are selected on the basis of the following requirements:

(1) Time delay $\leq$ 1 millisecond

(2) Adequate loop stability

(3) Maximum phase deviation in the APC loop during transient condition is not excessive.

(4) Smallest possible IF error consistent with loop stability.

(5) Adequate APC loop noise bandwidth (fixes APC gain and filter time constants.)

AFC Loop Gain = 1000 max.

AFC Compensation $= \dfrac{1 + .002s}{1 + s}$

APC Loop Gain = 4200

APC Compensation $= \dfrac{1 + .0133s}{1 + .2s}$

These values are based on the system requirements and realizability.

SYSTEM BLOCK DIAGRAMS

Figures 1 and 2 are block diagrams of the AFC and APC loops.

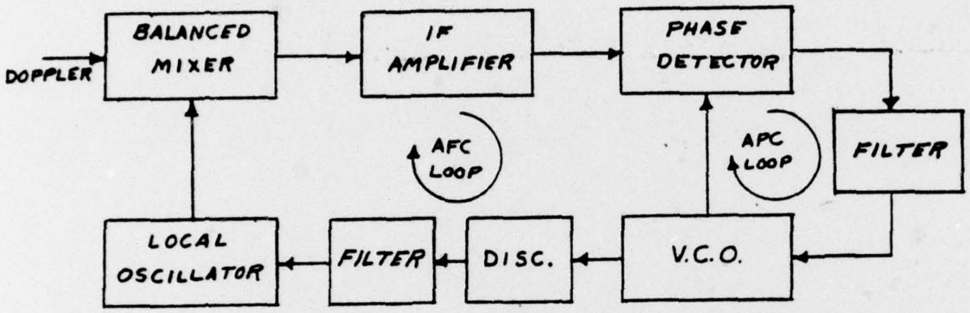


Figure 1
System Block Diagram

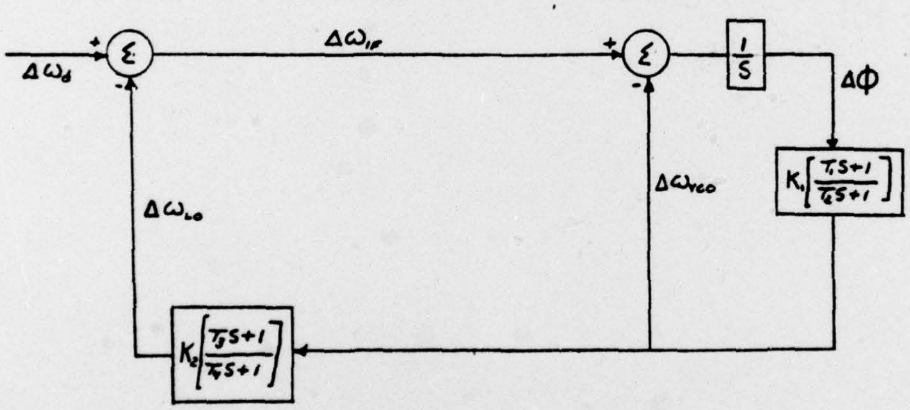


Figure 2
Linearized System Block Diagram

where

$\Delta\omega_d$ = change in doppler frequency

$\Delta\omega_{LO}$ = Local oscillator frequency shift

$\Delta\omega_{IF}$ = Error between doppler and local oscillator

$\Delta\omega_{vco}$ = Voltage controlled oscillator frequency shift

$\Delta\phi$ = Phase error between $\Delta\omega_{IF}$ and $\Delta\omega_{vco}$

K_2 = Disc. gain x local oscillator gain

K_1 = Phase detector gain x VCO gain

LINEARIZED SYSTEM TRANSFER FUNCTIONS

The transfer functions of interest, namely the IF error and the phase error, are derived. From Figure 2

$$\Delta\omega_{IF} = \Delta\omega_d - \Delta\omega_{LO} \tag{1}$$

$$\frac{\Delta\omega_{LO}}{\Delta\omega_d} = \frac{K_1K_2\,(T_1s+1)(T_3s+1)}{(T_4s+1)(T_2s^2+s(1+K_1T_1)+K_1)+K_1K_2(T_3s+1)(T_1s+1)} \tag{2}$$

Combining equations 1 and 2

$$\frac{\Delta\omega_{IF}}{\Delta\omega_d} = \frac{(s+\frac{1}{T_4})\,(s^2+s(\frac{1+K_1T_1}{T_2})+\frac{K_1}{T_2})}{(s+\frac{1}{T_4})\left[s^2+s(\frac{1+K_1T_1}{T_2})+\frac{K_1}{T_2}\right]+\frac{K_1K_2T_1T_3}{T_2T_4}(s+\frac{1}{T_1})(s+\frac{1}{T_3})} \tag{3}$$

Equation 3 is the expression for IF error as a function of the doppler input.

The phase error is obtained as follows

$$\frac{\Delta\omega_{vco}}{\Delta\omega_{IF}} = \frac{K_1\left[T_1\,s+1\right]}{T_2\,s^2+s(1+K_1T_1)+K_1} \tag{4}$$

$$\Delta\phi = \frac{1}{s}\,(\Delta\omega_{IF}-\Delta\omega_{vco}) \tag{5}$$

$$\Delta\omega_{LO} = \Delta\omega_{vco}\left[K_2\,\left(\frac{T_3\,s+1}{T_4\,s+1}\right)\right] \tag{6}$$

$$\Delta\omega_{IF} = \Delta\omega_d - \Delta\omega_{LO} \tag{7}$$

Combine equations 4, 5, 6 and 7 to obtain

$$\frac{\Delta \phi}{\Delta \omega_d} = \frac{(s + \frac{1}{T_4})(s + \frac{1}{T_2})}{(s + \frac{1}{T_4})\left[s^2 + s(\frac{1 + K_1T_1}{T_2}) + \frac{K_1}{T_2}\right] + \frac{K_1K_2T_1T_3}{T_2T_4}(s + \frac{1}{T_3})(s + \frac{1}{T_1})} \tag{8}$$

Equation 8 is the expression for the phase error as a function of doppler frequency input.

COMPUTATION OF PHASE LOCK LOOP NOISE BANDWIDTH

Bandwidth is defined as

$$BW = \int_0^{\infty} \left|y(f)\right|^2 df \tag{9}$$

The APC loop noise bandwidth is determined with the aid of the following equation (Reference (2)).

$$2BW_{cps} = I_N = \frac{1}{2\pi j} \int_{-j\infty}^{+j\infty} \frac{c(s)\ c(-s)}{d(s)\ d(-s)}\ ds \tag{10}$$

where

$$c(s) = c_{n-1}\ s^{n-1} + \dots c_o$$

$$d(s) = d_n\ s^n + d_{n-1}\ s^{n-1} + \dots d_o$$

The value of this integral in terms of the coefficients of a second order closed loop response is

$$I_2 = \frac{c_1^2\ d_o + c_o^2\ d_2}{2\ d_o d_1 d_2} \tag{11}$$

The APC loop has a closed loop transfer function

$$\frac{\Delta \omega_{vco}}{\Delta \omega_{if}} = \frac{K_1\left[T_1 s + 1\right]}{\left[T_2 s^2 + s(1 + K_1T_1) + K_1\right]} \tag{12}$$

Therefore from equation 12 the coefficients are defined

$$c_1 = K_1T_1 \qquad c_o = K_1$$

$$d_2 = T_2 \qquad d_1 = (1 + K_1T_1) \qquad d_o = K_1$$

with

$$K_1 = 4200 \qquad T_2 = .2 \qquad T_1 = 1.33(10^{-2})$$

The noise bandwidth results after substitution in equation (11)

$$2BW_N = \frac{\left[(4200)(1.33 \times 10^{-2})\right]^2 4200 + (4200)^2(.2)}{(2)(.2)\left[1 + (4200)(1.33 \times 10^{-2})\right] 4200} \qquad (13)$$

$$2BW_N = 174 \text{ cycles/sec}$$

SYSTEM TRANSIENT RESPONSE COMPUTED ON THE DIGITAL COMPUTER

Equations 3 and 8 will now be used with several trial sets of parameters in order to gain an insight as to the effect of the lag-lead network in the AFC portion of the loop. The APC loop noise bandwidth will essentially be fixed at approximately 200 cycles/sec. APC loop gain will be kept high so that noise degradation, pull-in performance, and hold in performance are adequate (Reference (1)). The AFC gain will be high so that system performance will not be to impaired as a result of the local oscillator gain change with frequency.

Table 1 summarizes the parameters used in computing the transient responses. Table 2 gives the figure numbers for the transient response plots.

Case	K_1	K_2	$1/T_1$	$1/T_2$	$1/T_3$	$1/T_4$	APC 2BW
1	7500	500	141	5.34	173	.333	200 cps
2	7500	1000	141	5.34	173	.333	"
3	4200	500	75	5	500	10	174 cps
4	4200	1000	75	5	500	10	"

TABLE 1

Case	$\Delta\phi$	$\Delta\omega_{IF}$	Comments
1	Figure 6	Figure 4	Large phase overshoot Large IF error Heavy filtering AFC loop
2	Figure 7	Figure 5	If error reduced by 2 Phase error reduced by 2
3	Figure 9	Figure 8	Phase overshoot reduced IF error greatly reduced AFC filtering reduced
4	Figure 9	Figure 8	IF and phase error reduced by 2

TABLE 2

Case 1

$K_2 = 500$ $\frac{1}{T_4} = 0.333$ radians $1/T_3 = 173$ radians

$K_1 = 7500$ $\omega_{N_{APC}} = 200$ radians/sec $\zeta_{APC} = 0.707$

$\frac{1}{T_1} = 141$ radians $\frac{1}{T_2} = 5.35$ radians

$$\frac{\Delta\omega_{IF}(s)}{\Delta\omega_d(s)} = \frac{(s + .333)\,(s^2 + 283s + 4(10^4)}{s^3 + 5.48333(10^2)s^2 + 1.245(10^5)s + 6.69(10^6)} \qquad (14)$$

$$\frac{\Delta\phi}{\Delta\omega_d} = \frac{(s + 5.34)\,(s + .333)}{s^3 + 5.48333(10^2)s^2 + 1.245(10^5)s + 6.69(10^6)} \qquad (15)$$

The resulting time solutions for a unit ramp doppler are

$$\Delta\omega_{IF}(t) = .596(10^{-2}) + .199(10^{-2})t - .547(10^{-2})\epsilon^{-75.25t} + .264(10^{-2})\epsilon^{-236.5t} \sin(181.5t + 6.10) \qquad (16)$$

$$\phi(t) = .843(10^{-6}) + .2658(10^{-6})t + .1569(10^{-4})\epsilon^{-75.25t} + .2235(10^{-6})\epsilon^{-236.5t}\sin(181.5t+3.97) \quad (17)$$

Case 2

$K_2 = 1000$ $\quad \frac{1}{T_4} = 0.33$ radians $\quad 1/T_3 = 173$ radians

$K_1 = 7500$ $\quad \omega_{N_{APC}} = 200$ radians/sec $\quad \zeta_{APC} = 0.707$

$\frac{1}{T_2} = 5.35$ radians $\quad \frac{1}{T_1} = 141$ radians

$$\frac{\Delta\omega_{IF}(s)}{\Delta\omega_d(s)} = \frac{(s + .333)(s^2 + 283\,s + 4(10^4))}{s^3 + 8.1333(10^2)s^2 + 2.0944(10^5)s + 1.392(10^7)} \quad (18)$$

$$\frac{\Delta\phi}{\Delta\omega_d}(s) = \frac{(s + 5.34)(s + .333)}{s^3 + 8.1333(10^2)s^2 + 2.0944(10^5)s + 1.392(10^7)} \quad (19)$$

The time solutions for a unit ramp input are

$$\Delta\omega_{IF}(t) = .287(10^{-2}) + .957(10^{-2})t - .282(10^{-2})\epsilon^{-101.4t} + .678(10^{-2})\epsilon^{-356t}\sin(102.6t + 6.28) \quad (20)$$

$$\Delta\phi(t) = .407(10^{-6}) + .128(10^{-6})t + .125(10^{-4})\epsilon^{-101.4t} + .350(10^{-4})\epsilon^{-356t}(\sin(102.6t+3.52) \quad (21)$$

Plots of equations 16, 17, 20 and 21 are presented in Figures 4, 5, 6 and 7. Cases 1 and 2 are an example of an APC loop noise bandwidth of 200 cycles with heavy filtering on the discriminator output.

Case 3

$K_1 = 4200$ $\quad 1/T_1 = 75$ radians $\quad 1/T_2 = 5$ radians

$K_2 = 500$ $\quad 1/T_3 = 500$ $\quad 1/T_4 = 10$ radians

$$\frac{\Delta\omega_{IF}(s)}{\Delta\omega_d(s)} = \frac{(s+10)\,(s^2+283s+2.1(10^8)}{s^3+3.093(10^3)s^2+1.63128(10^6)s+1.0521(10^8)} \tag{22}$$

$$\frac{\Delta\phi(s)}{\Delta\omega_d(s)} = \frac{(s+5)\,(s+10)}{s^3+3.093(10^3)s^2+1.63128(10^6)s+1.0521(10^8)} \tag{23}$$

The time solutions for a unit ramp input are

$$\Delta\omega_{IF}(t) = .1955(10^{-3})+.199(10^{-2})t-.529(10^{-4})\epsilon^{-74.86t}$$
$$+.346(10^{-3})\epsilon^{-575.3t}-.488(10^{-3})\epsilon^{-2442.8t} \tag{24}$$

$$\Delta\phi(t) = .135(10^{-6})+.475(10^{-6})t+.682(10^{-6})\epsilon^{-74.86t}$$
$$-.104(10^{-5})\epsilon^{-575.3t}+.225(10^{-6})\epsilon^{-2442.8t} \tag{25}$$

Case 4

$K_1 = 4200$ $\quad 1/T_1 = 75$ radians $\quad 1/T_2 = 5$ radians

$K_2 = 1000$ $\quad 1/T_3 = 500$ radians $\quad 1/T_4 = 10$ radians

$$\frac{\Delta\omega_{IF}(s)}{\Delta\omega d(s)} = \frac{(s+10)\,(s^2+283s+2.1(10^4))}{s^3+5.893(10^3)s^2+3.24128(10^6)s+2.1021(10^8)} \tag{26}$$

$$\frac{\Delta\phi(s)}{\Delta\omega_d(s)} = \frac{(s+10)\,(s+5)}{s^3+5.893(10^3)s^2+3.24128(10^6)s+2.1021(10^8)} \tag{27}$$

The resulting time solutions for a unit ramp input are

$$\Delta\omega_{IF}(t) = .979(10^{-4})+10^{-3}t-.263(10^{-4})\epsilon^{-74.93t} + .130(10^{-3})\epsilon^{-530.6t} -.202(10^{-3})\epsilon^{-5297.5t} \qquad (28)$$

$$\Delta \phi(t) = .677(10^{-7})+.238(10^{-6})t+.341(10^{-6})\epsilon^{-74.93t} - .448(10^{-6})\epsilon^{-530.6t} +.402(10^{-7}\epsilon^{-5287.5t} \qquad (29)$$

Figures 8 and 9 present plots of equations 24, 25, 28 and 29.

COMPUTATION OF MAXIMUM TRACKING RATE

The values of $\phi(t)$ may be obtained from Figures 6 and 9 for unit ramp changes in the doppler frequency and substituted in the following equation to find the value of the phase error in degrees.

$$\phi(t)\text{degs.} = 2\pi\dot{f}\ \phi(t)\frac{180}{\pi} = 360\ \dot{f}\ \phi(t)\Big|_{\text{radians}} \qquad (30)$$

where

$\dot{f}$ = change in doppler frequency in cycles/second/second

from Figure 6 $\phi(t)\Big|_{\text{radians}}$ at 5 milliseconds = $7.15(10^{-6})$

from Figure 9 $\phi(t)\Big|_{\text{radians}}$ at 5 milliseconds = $.55(10^{-6})$

If 30 degrees is the maximum phase error allowed for good detection and the transient value is the limiting condition, then from Figure 6

$$\dot{f}_{\max} = \frac{30}{360\ \phi(t)\Big|_{.005\ \text{sec}}} = \frac{30}{(3.60)(7.15)(10^{-4})}$$

$$= 1.165(10^{4}) = 11.65\text{KC/sec/sec} \qquad (31)$$

and from Figure 9

$$\dot{f}_{\max} = \frac{30}{360\ \phi(t)\Big|_{.005\ \text{sec}}} = \frac{30}{(3.6)(.55)}10^{4} = 151\ \text{KC/sec/sec} \qquad (32)$$

These values are obtained for an AFC gain of 500. The IF error can be obtained from Figures 4 and 8 with the aid of the following equation $\Delta f_{IF} = \dot{f}\, f(t)$. For example, from Figure 8

$$f(t)\Big|_{1.3\ \text{sec}} = 2.80(10^{-3}) \text{ for } K_{AFC} = 500$$

$$\Delta f_{IF} = 2.80\ (10^{-3})\ 151(10^{3}) = 424 \text{ cycles/seconds}$$

$\dot{f}_{max}$ (KC/sec/sec)	$\Phi_{TRANS.}$	IF ERROR @ 1.3 sec.	$\frac{1}{T_4}$	$\frac{1}{T_3}$	$\frac{1}{T_2}$	$\frac{1}{T_1}$	K_1	K_2	2BW NOISE BW APC LOOP
11.65	30°	99 cps	.33	173	5.35	141	7500	500	200 cps
151	30°	424 cps	10	500	5	75	4200	500	174 cps

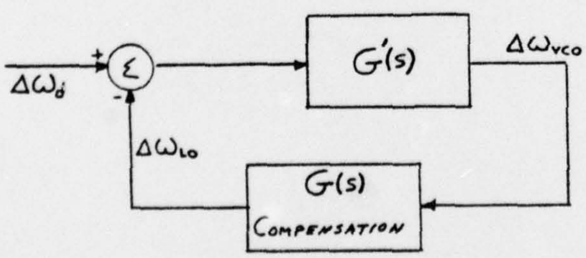
TABLE 3

Table 3 illustrates the increase in tracking rate as $1/T_4$ is increased with the maximum phase transient allowable not to exceed 30 degrees. This increase in tracking ability is to be expected since the system bandwidth is increased with an increase in $1/T_4$.

LINEAR STABILITY ANALYSIS

The system without time delay presents no stability problem. The addition of the system time delay (phase lag) modifies the phase characteristics of the APC loop to the extent that unstable operation results when any realistic AFC gain is used.

The loop phase and gain margin will now be investigated in conjunction with several forms of compensation. Consider the following loop:



where $G'(s)$ is the closed APC loop phase and gain response with a 1 millisecond time delay (Figure 11). Consider the case when $G(s) = \frac{s + 1}{s + 500}$ (Figure 12). The resulting open loop response (Figure 13) indicates that with $K_{AFC} = 60$ db the phase margin is 30 degrees and the gain margin is 12 db. This compensation provides adequate performance. If compensation of the form $G(s) = \frac{(s + 200)(s + 400)}{(s + 2)(s + 4000)}$ is used (Figure 14), the open loop response is shown in Figure 15. A comparison of the results obtained in using the two types of compensation clearly indicate that $G(s)$ should be $\frac{T_3\, s + 1}{T_4\, s + 1}$ in order to obtain stable performance.

EFFECT OF NON-LINEAR LOCAL OSCILLATOR ON IF ERROR

The data presented is given for two specific AFC gain values, which are the local oscillator limits for a 100 KC deviation. It is intended that the oscillator will be positioned at launch such that the AFC gain will be 1000. As noted from a comparison of cases 1 and 2 or cases 3 and 4 there is a reduction in the IF transient with an increase in AFC gain. In all cases presented, the IF error build-up is equal to $1/K_{AFC}$. This indicates the need for a high AFC gain, which at present has a realizable value of 1000. The phase build-up is inversely proportional to the product gain K_1K_2.

Figure 10 is obtained from Figure 3 in the following manner: (1) the local oscillator starting frequency is 700KC and increasing (2) lines are drawn with slope $1/K_{AFC}$, where K_{AFC} is (L.O. gain)(Summer gain)(Discriminator gain), for every 10KC change in oscillator frequency (3) IF error build-up curves can be constructed by assuming a doppler rate, therefore changing to a different slope at the correct time interval, i.e. 100 KC/sec rate changes to a new Δ F line every .1 seconds. The IF error at 1.3 seconds is obtained from Figure 10 for a 100 KC/sec/sec ramp input as

$$IF_{error} = \text{transient} + 4.7(10^{-3}) \text{ for a unit ramp input}$$

$$= \text{transient} + 470 \text{ cps for a 100 KC/sec ramp input}$$

If the gain were a constant the build-up would be 210 cycles/second since the slope would be that corresponding to $\Delta F = 0$. This increase in IF error build-up justifies the initial negative IF offset to allow the large variation without exceeding the IF bandwidth.

The transient will add considerably to the total error. As seen from the case 1 the transient is $5.96(10^{-3})\dot{f}$, which in the previous example would add 596 cps of error. Therefore the maximum doppler rate is limited and clearly illustrates the fact that aided tracking is essential. This is also borne out by the fact that the compensation requirement is dictated by the time delay which results in a pole at approximately 1 radian in the AFC loop and a large IF transient.

AIDED TRACKING

Aided tracking will probably be accomplished by summing a fraction of the rear signal with the error signal presented to the local oscillator. The data presented in this memo can be used in conjunction with aided tracking by merely multiplying the values for the IF and phase error by (1 - x), where x is the fraction of the rear signal used for aided tracking.

CONCLUSIONS

The narrow-band system is not adequate for the tracking rates which will be encountered unless good aided tracking is used. It has been noted that tracking ability has been improved with an increase in $1/T_4$, but $1/T_4$ max. is limited by the 1 millisecond time delay. The maximum tracking rate obtainable is specified by the maximum phase error (30°). This allows a threshold of approximately 50 degrees for noise variations and still maintain lock conditions.

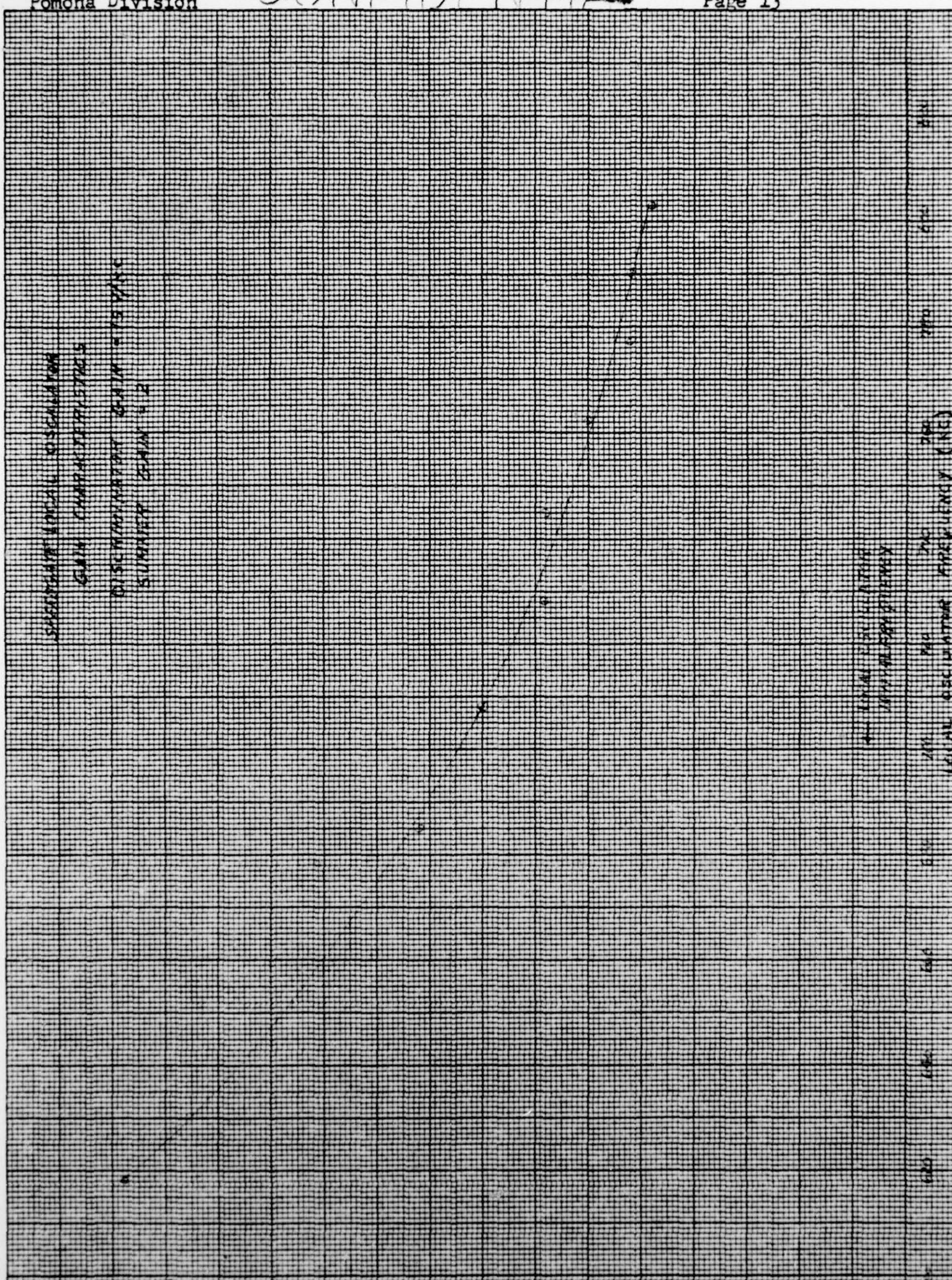


FIGURE 3

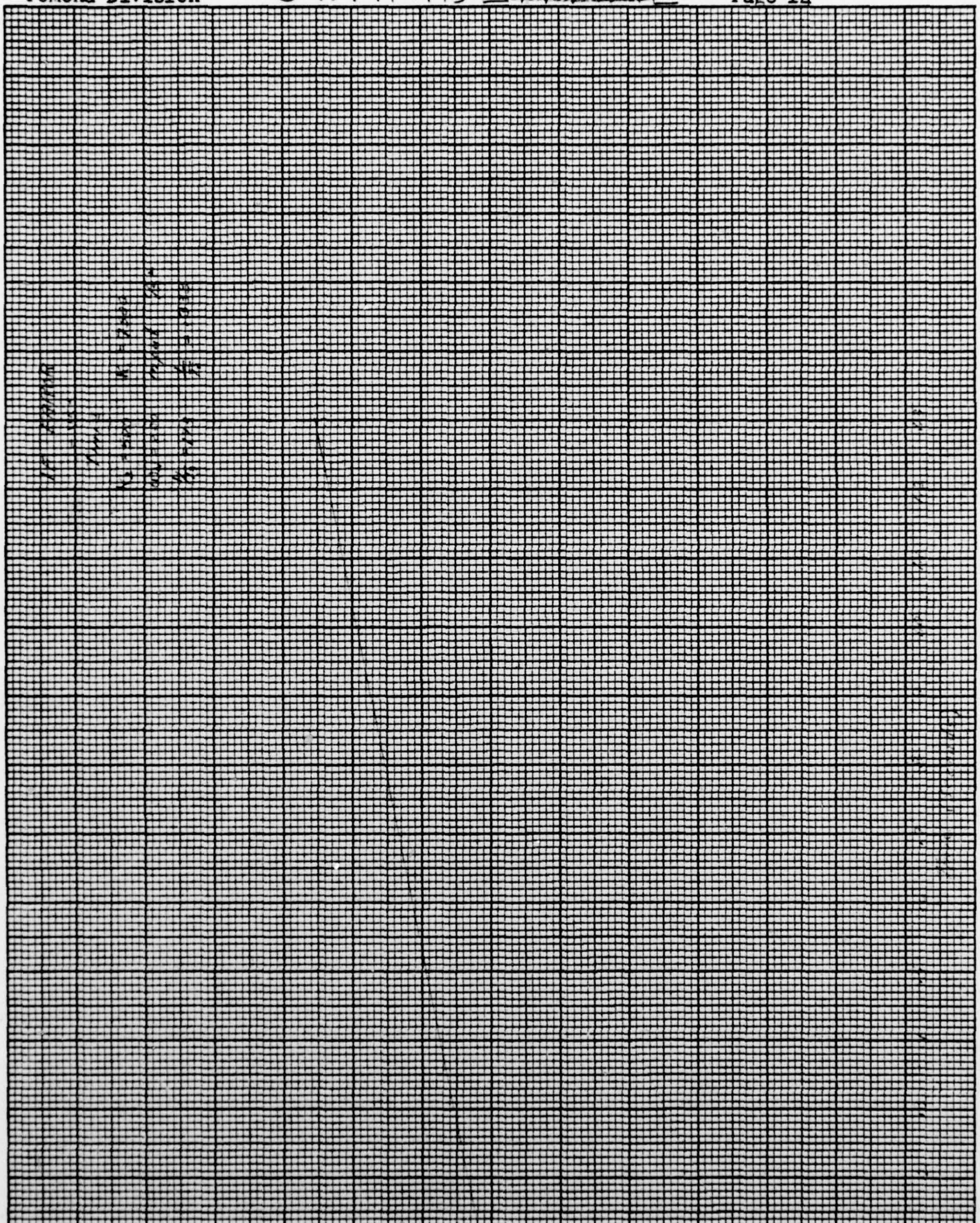


FIGURE 4

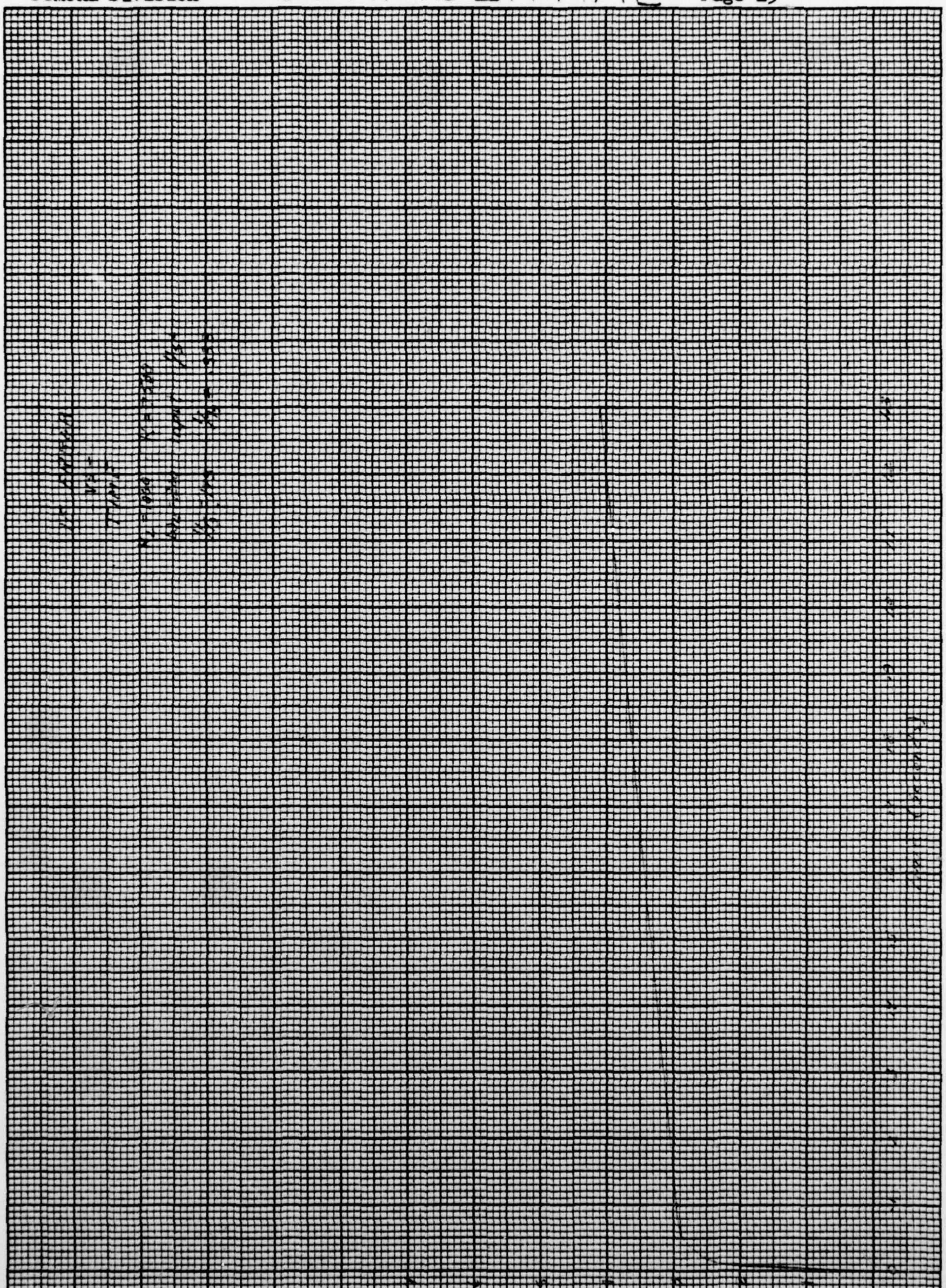


FIGURE 5

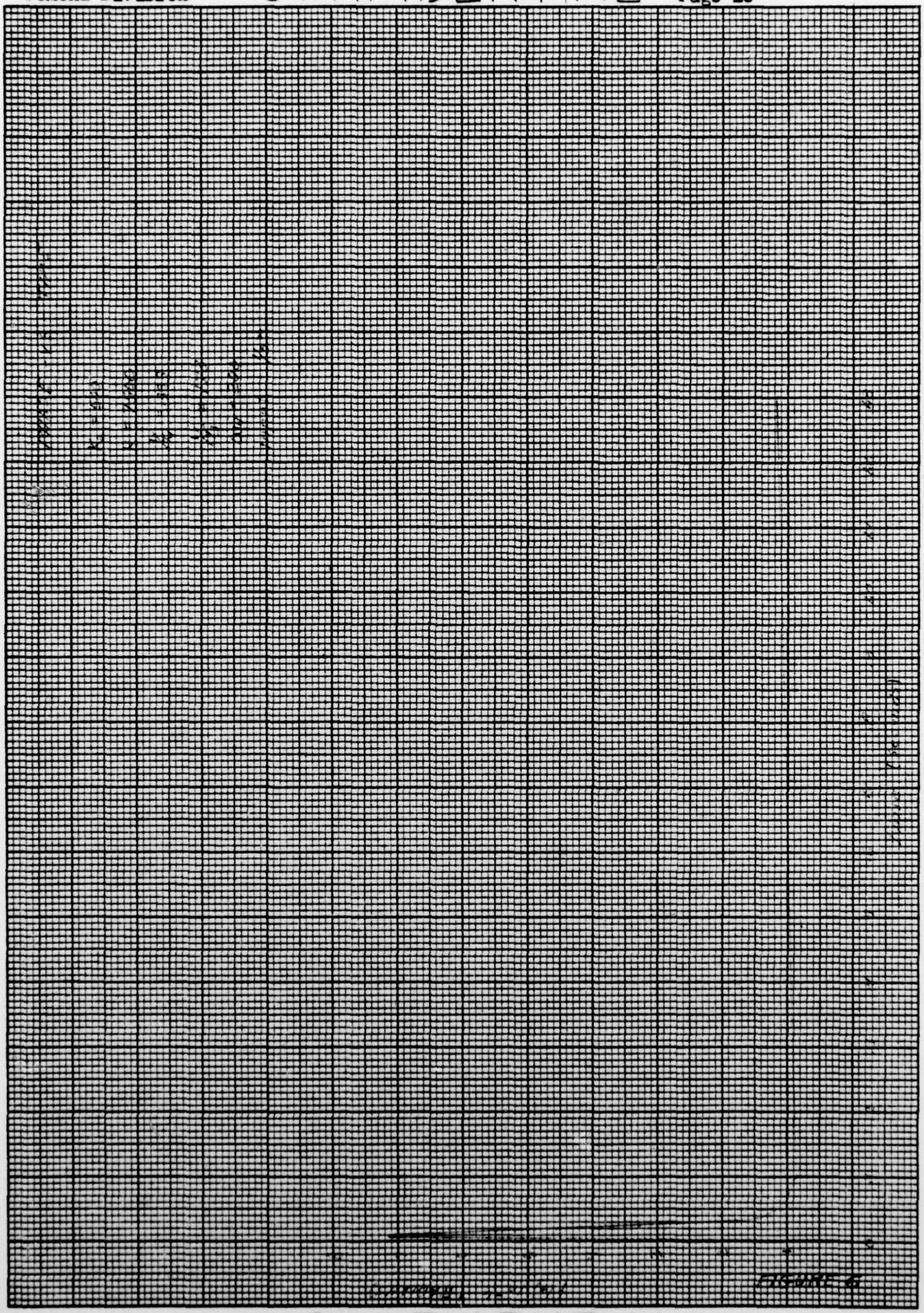


FIGURE 6

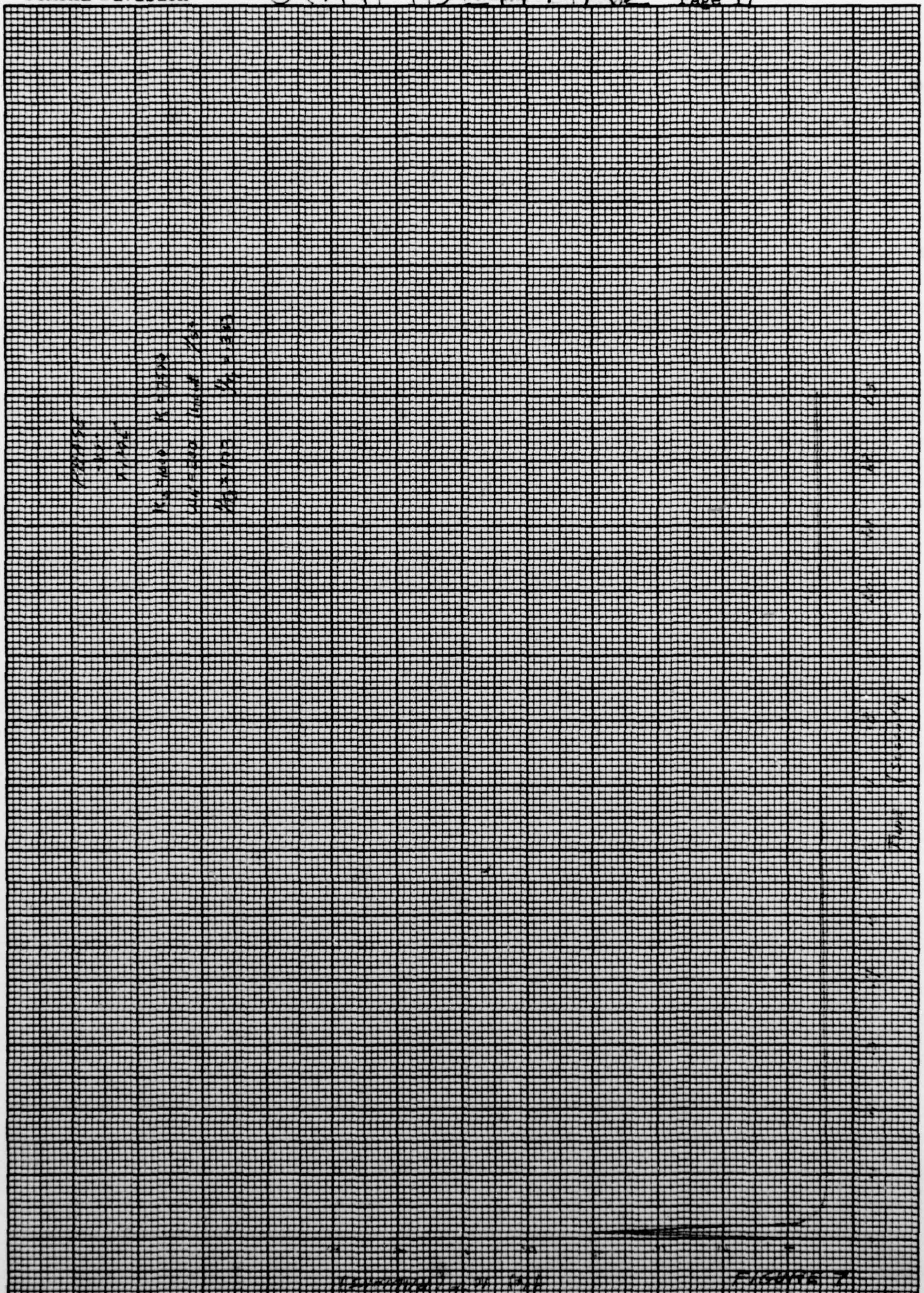


FIGURE 7

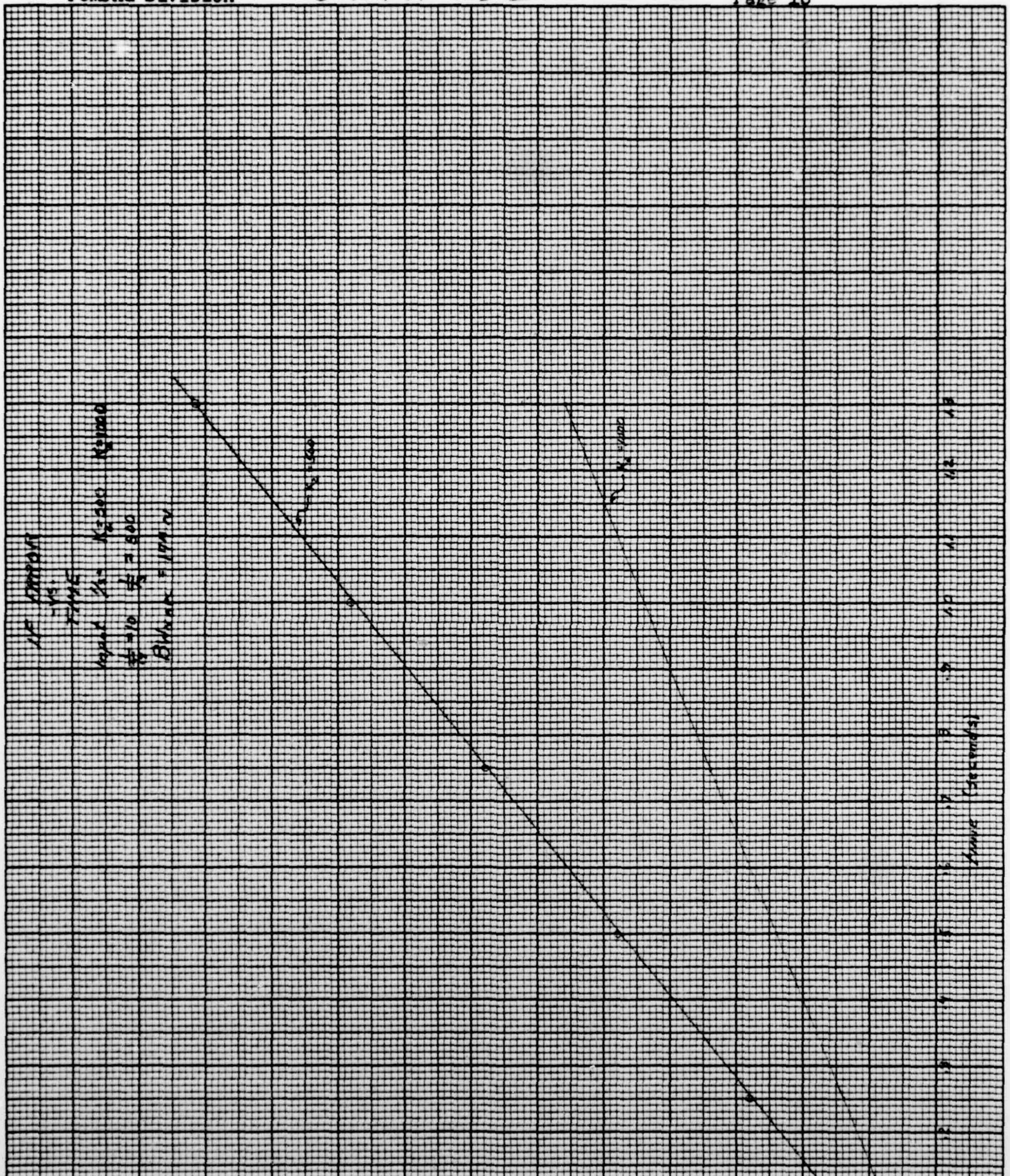


FIGURE 8

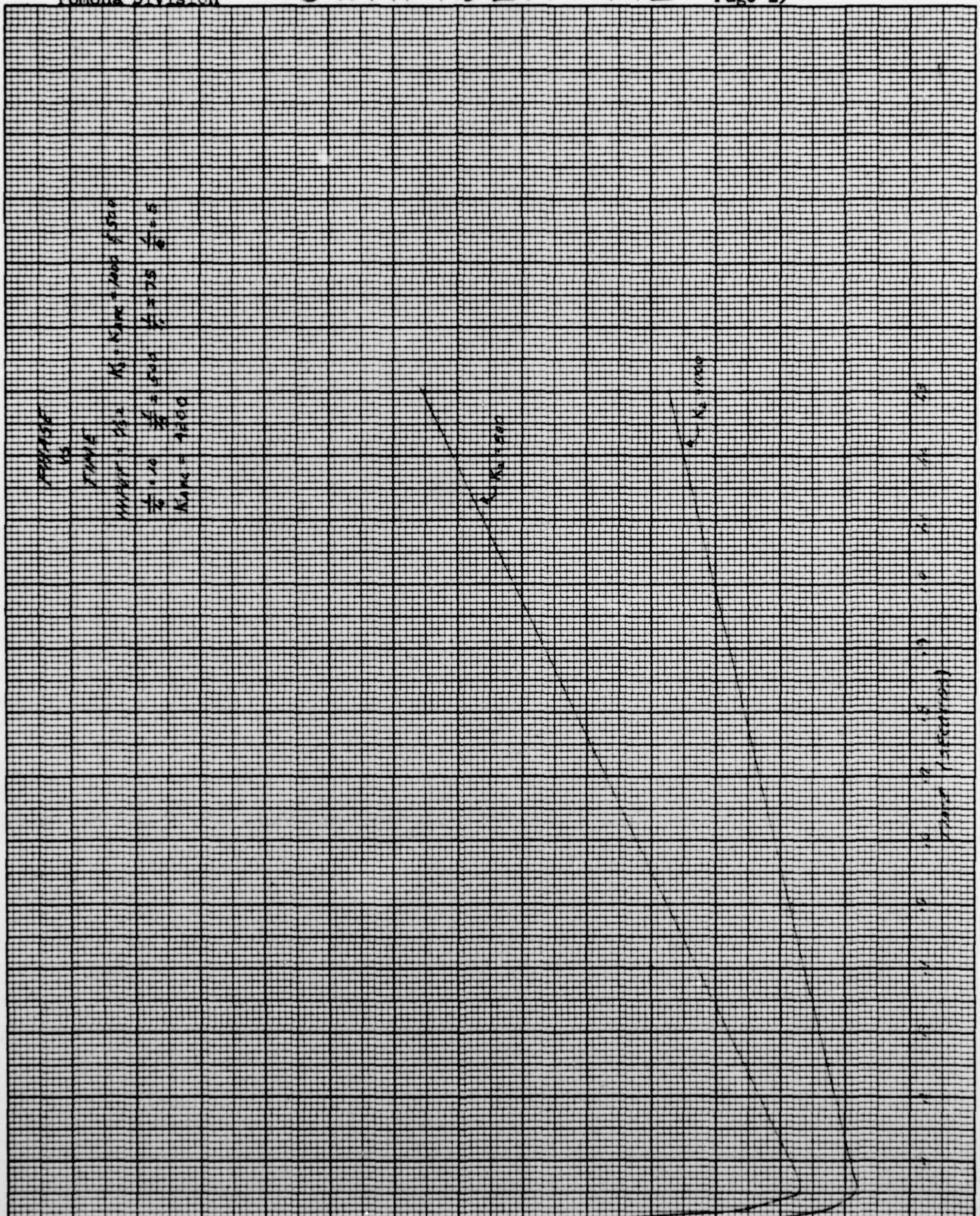


FIGURE 3

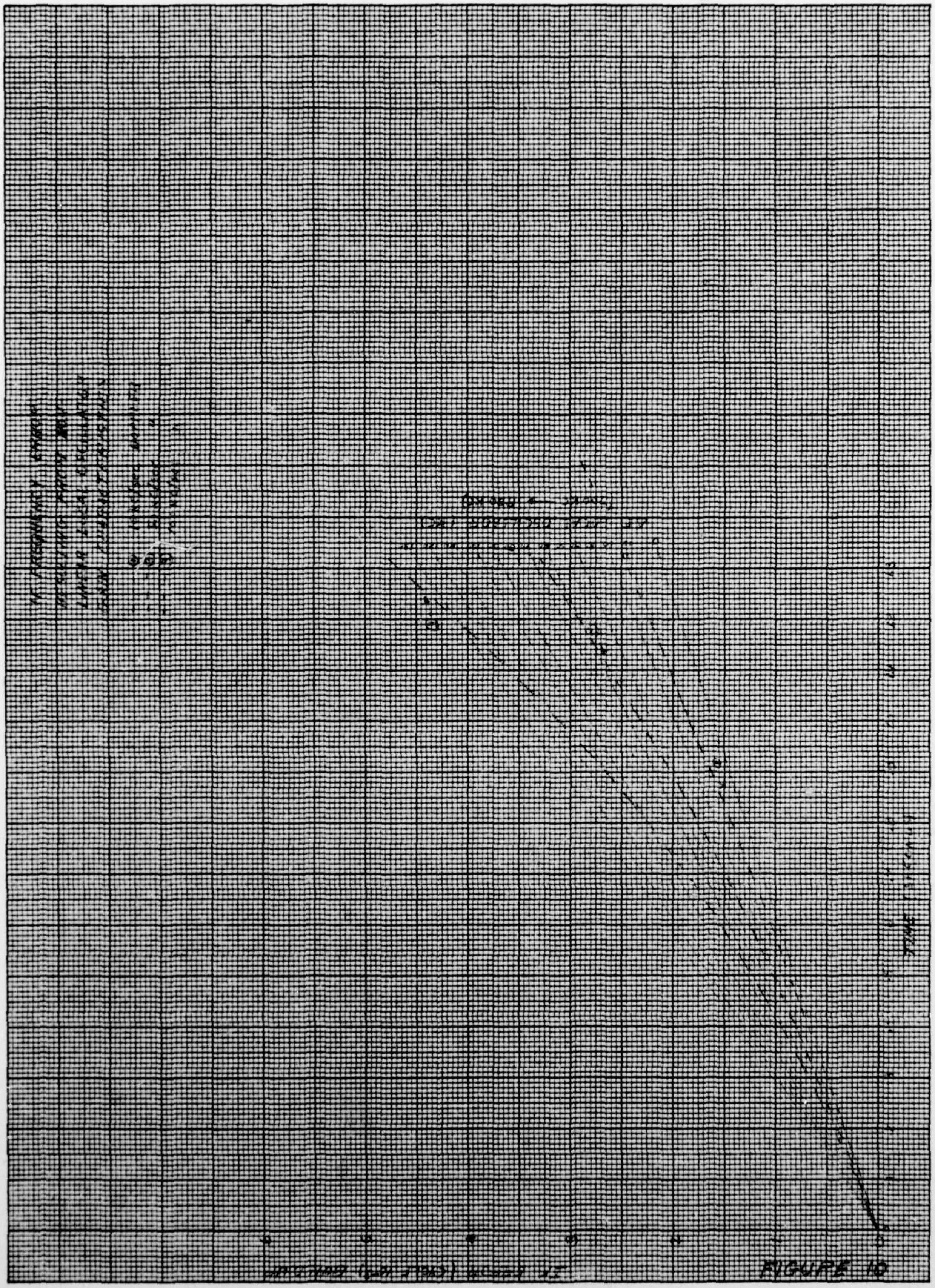
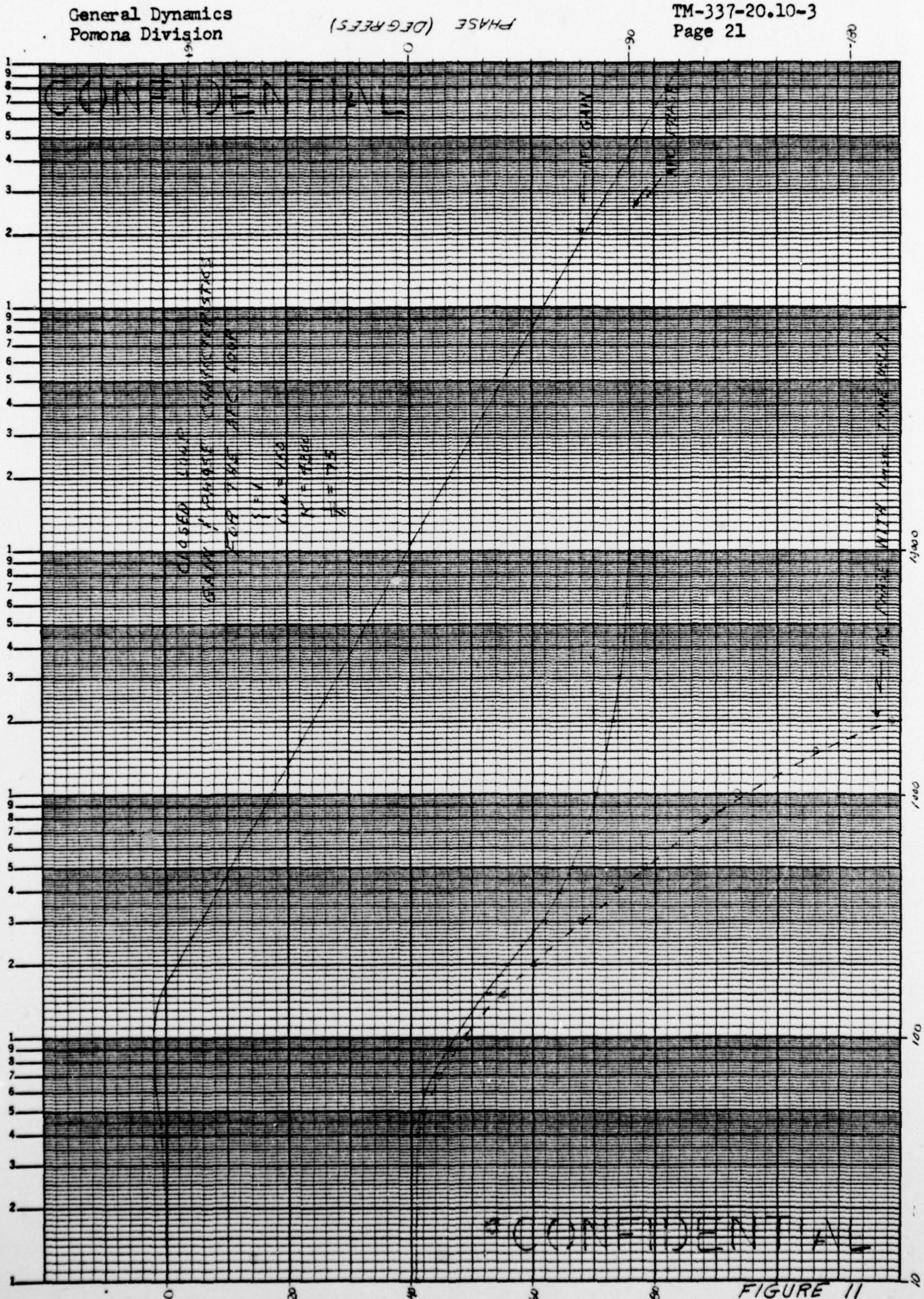


FIGURE 10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PHASE (DEGREES)
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-90
-180
AFC GAIN
AFC PHASE
CLOSED LOOP
GAIN & PHASE CHARACTERISTICS
FOR THE AFC LOOP
GAIN DB
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FIGURE 11

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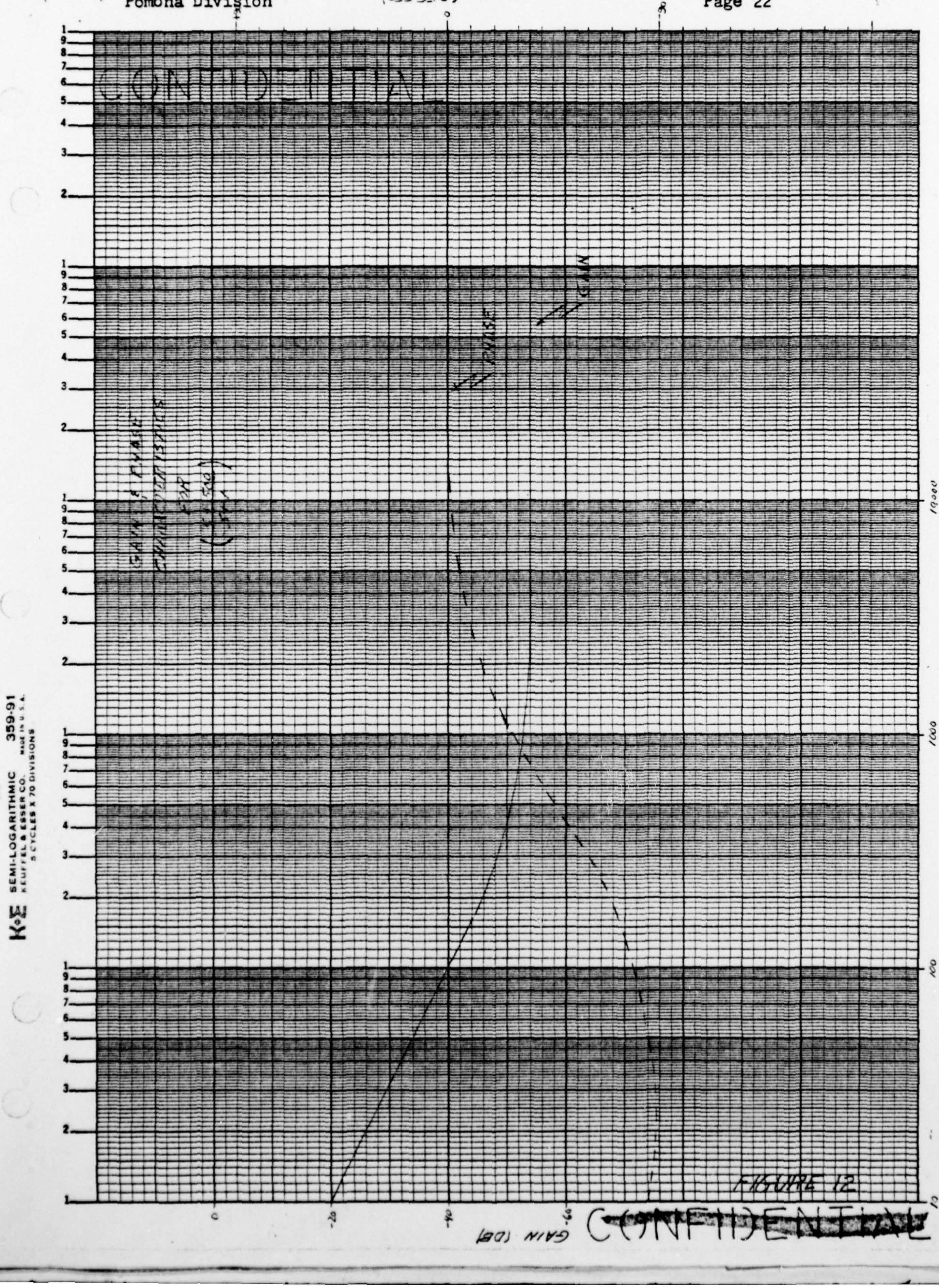

FIGURE 12

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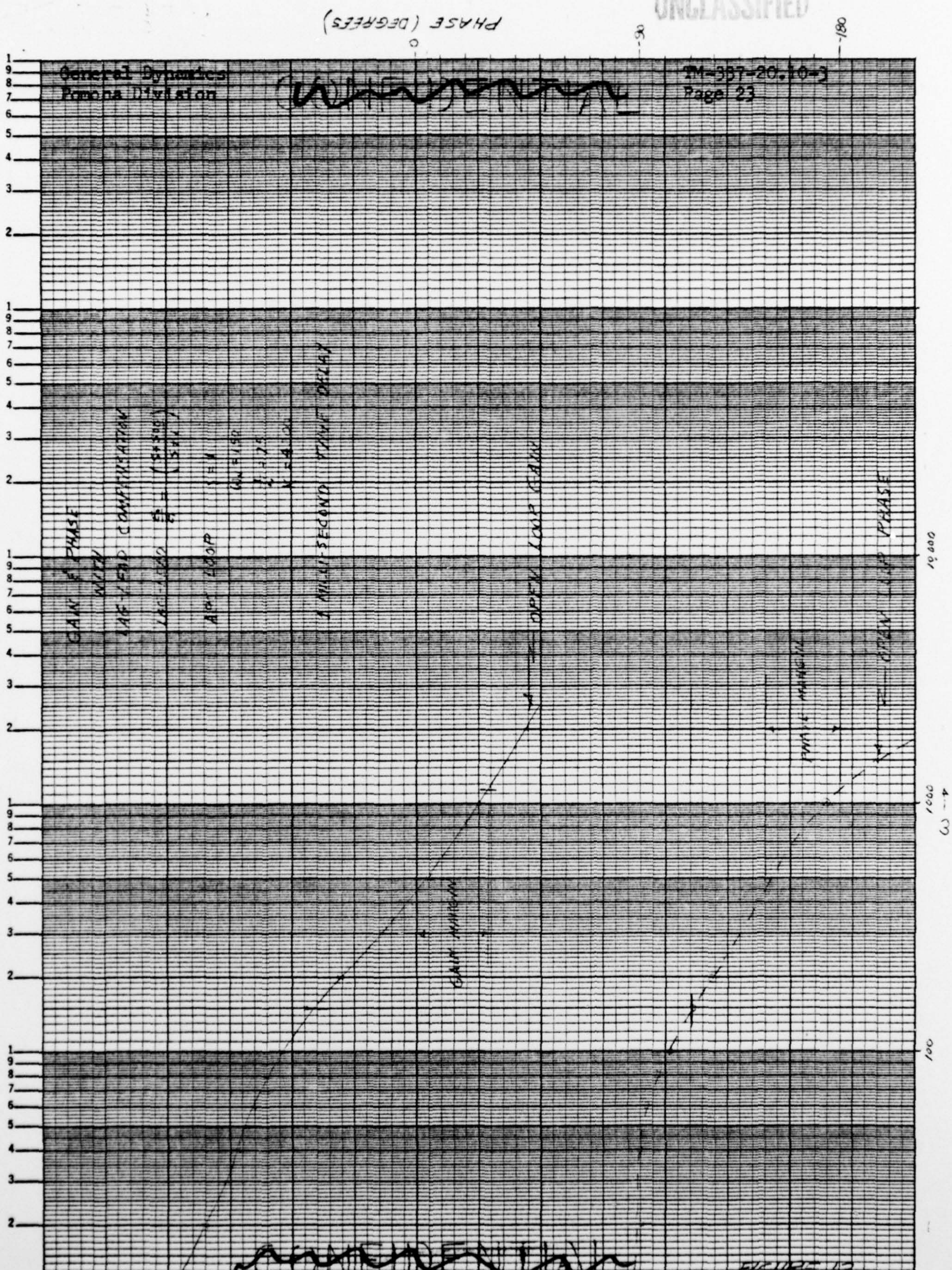

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FIGURE 13

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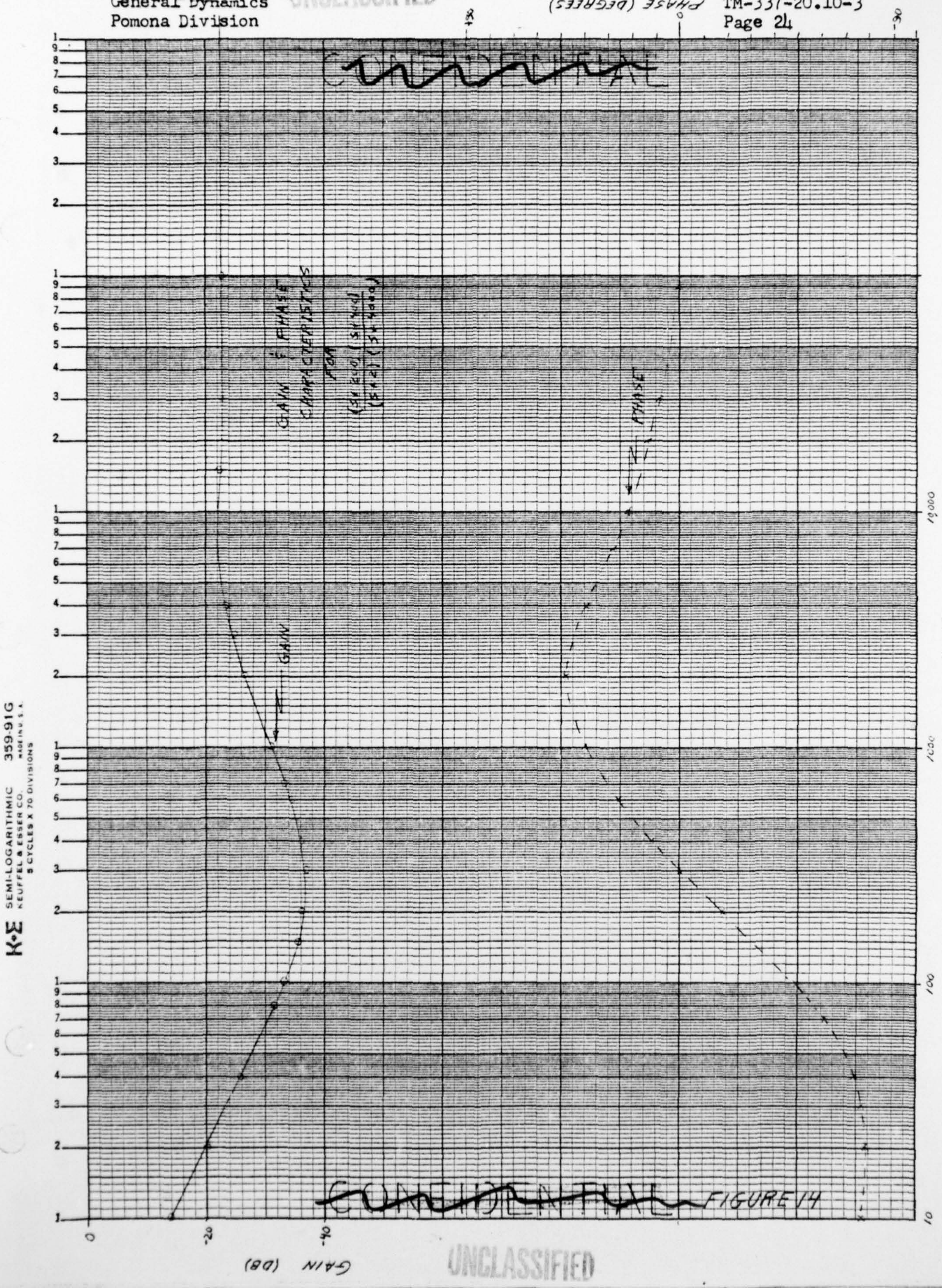
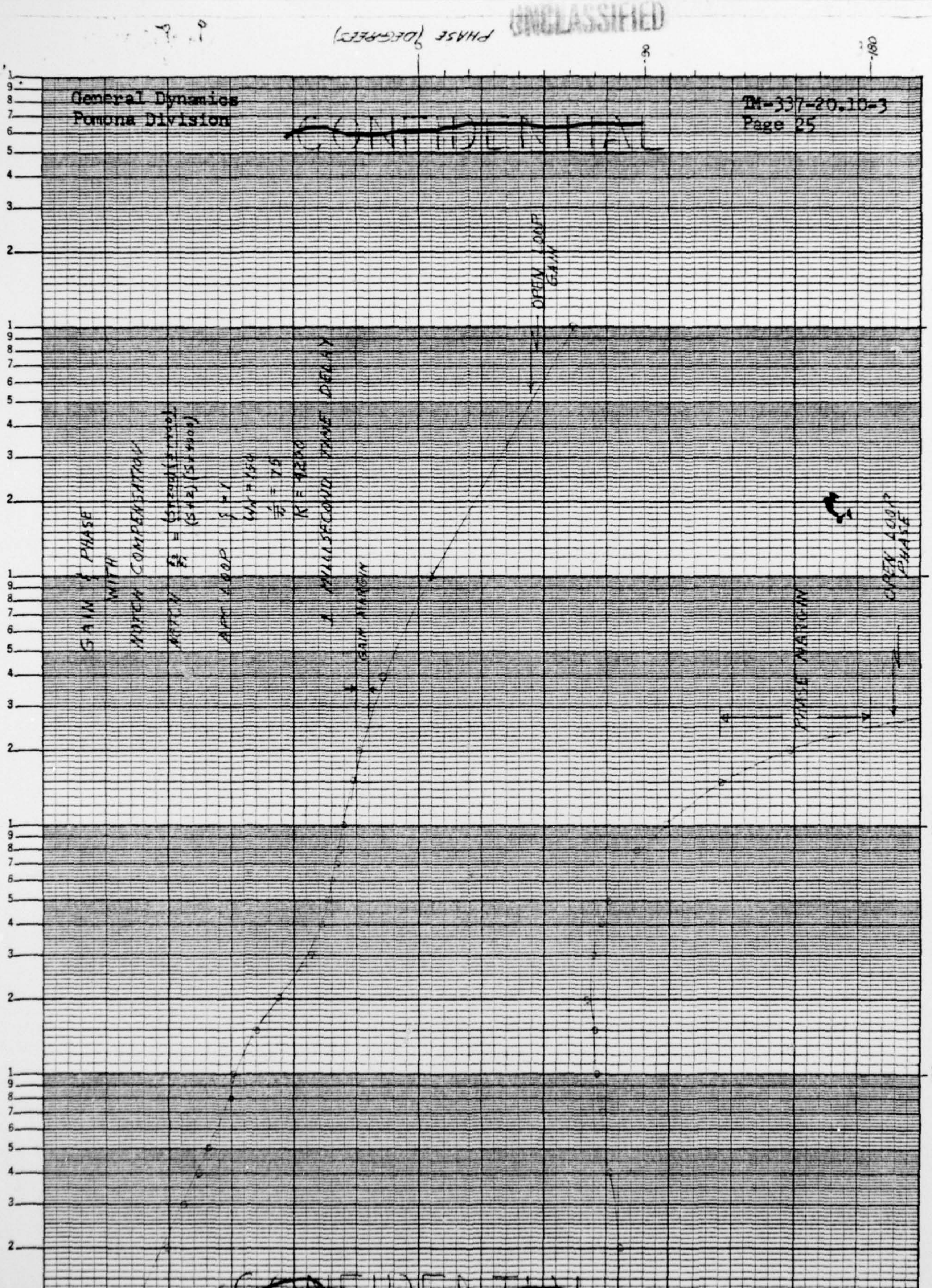


~~CONFIDENTIAL~~ FIGURE 14

~~CONFIDENTIAL~~



~~CONFIDENTIAL~~

FIGURE 15

K&E SEMI-LOGARITHMIC 359-91G
KEUFFEL & ESSER CO. MADE IN U.S.A.
5 CYCLES X 70 DIVISIONS